APPLICATIONS OF THE STRATEGIC DEFENSE INITIATIVE'S COMPACT ACCELERATORS

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ABSTRACT

The Strategic Defense Initiative's (SDI) investment in particle accelerator technology for its directed energy weapons program has produced breakthroughs in the size and power of new accelerators. These accelerators, in turn, have produced spinoffs in several areas: the radio frequency quadrupole linear accelerator (RFQ linac) was recently incorporated into the design of a cancer therapy unit at the Loma Linda University Medical Center, an SDI-sponsored compact induction linear accelerator may replace Cobalt-60 radiation and hazardous ethylene-oxide as a method for sterilizing medical products, and other SDIO-funded accelerators may be used to produce the radioactive isotopes oxygen 15, nitrogen 13, carbon 11, and fluorine 18 for positron emission tomography (PET). Other applications of these accelerators include bomb detection, non-destructive inspection, decomposing toxic substances in contaminated ground water, and eliminating nuclear waste.

INTRODUCTION

Particle accelerators, devices that produce high-energy beams of charged atomic or sub-atomic particles, have largely been limited to research applications due to their high cost. SDI, however, has focused much attention on developing low-cost, reliable particle accelerators as part of a system to provide protection against ballistic missile attacks. As a result, several SDI-funded researchers are developing ways to reduce the size, weight, and cost and increase the reliability of particle accelerators that drive free electron lasers, neutral particle beams, and other directed energy weapons. As a result of these improvements, SDI-funded accelerators have a variety of spinoff applications.

Researchers have long known accelerator technology could be used for a number of medical and industrial applications such as providing treatments for cancer and other ailments, sterilizing medical products, production of isotopes for PET imaging, non-destructive inspection and testing, industrial welding, environmental clean-up, and electron-beam processing. Widespread application has never been achieved, however, due to limitations in accelerator technology that prevented them from replacing alternative techniques, such as employing radioactive sources. Thus, the same improvements in size, weight, and cost sought by SDI would benefit these commercial applications. As a result, several accelerators developed with SDI funding have made these applications a near-term reality instead of the dream of a few research accelerator physicists.

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APPLICATIONS

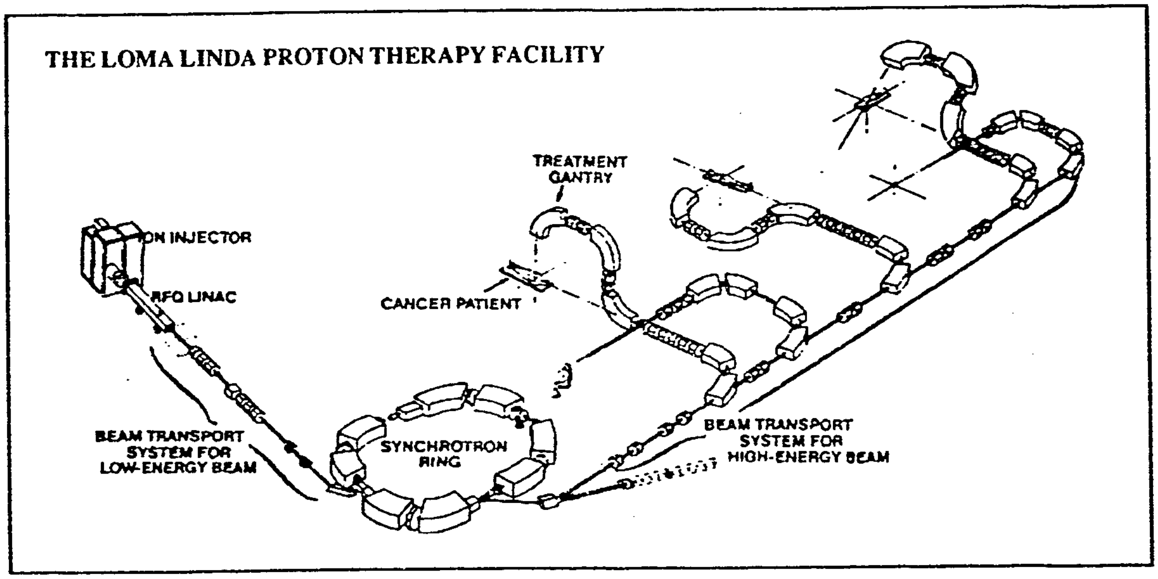
Proton Cancer Treatment at Loma Linda

The radio frequency quardupole linear accelerator (RFQ linac) — a key component of SDI's neutral particle beam program — now serves as the first stage of a high-energy proton accelerator operating at the Loma Linda University Medical Center to treat cancer.[2] Proton cancer therapy can treat a wide range of tumors — from those in the digestive system to those in the eye and brain. In addition, proton therapy is safer than conventional radiation or chemotherapy. The second two techniques both kill cancerous cells; however, because therapists have very little control over where these treatments are deposited, they are also more likely to damage adjacent healthy tissue. In fact, for some deep tumors, the treatment attacks more intervening healthy tissue than the tumor itself. As a result, the therapist often lowers the dose to the tumor to prevent excessive damage to surrounding tissue. This conservative approach may allow the tumor to continue to grow.

In contrast, therapists can precisely control proton beams. This is because proton beams deposit nearly all their energy at the target with little scattering. Also, since protons are charged particles, the therapist can more precisely control a proton beam's path than other forms of commonly used radiation (e.g. x-rays, gamma rays). In addition, protons produce much less damage to adjacent healthy tissue, making it possible to administer protons in higher doses. As a result, this treatment more thoroughly destroys the tumor with less side effects.

Other proton threapy facilities are also planned for Massachusetts General Hospital and the University of California at Berkeley.

Figure 1. The Loma Linda Proton Therapy Facility



Sterilization of Medical Products

Technologists have studied electron-beam conversion to x-ray radiation as a method to sterilize medical products for the last three decades. This method, however, has not been economically feasible, since the accelerator technology required to produce the electron-beams has never been competitive with chemical and radioisotopic methods of sterilization. In recent years, though, electron-beam sterilization has become a more viable alternative. Chemical sterilization using

[2] AccSys Technology, Inc. provided the RFQ linac injector for this facility, while Science Applications International Corporation (SAIC) installed the entire synchrotron system. Both companies have done extensive work on accelerators for SDI which contributed to this project.

ethylene oxide (ETO), is losing favor because ETO is an extremely explosive gas that must be stabilized with a buffer of chloro-fluorocarbons (CFCs). Because CFCs are associated with destruction of the ozone layer, recent legislation has placed a 100 percent tax on use of ETO gas mixtures and mandated almost complete recovery of CFCs. In addition, the EPA has strongly discouraged use of ETOs and perhaps may ban all but essential use of ETOs within the next decade.

Radioisotopic sterilization uses Cobalt 60 to produce x-ray radiation to sterilize medical products. Nordian International, a crown corporation of the Canadian Government, supplies 80 percent of all Cobalt 60, which is produced by neutron absorption of Cobalt 59 in nuclear reactors. The cost of Cobalt 60 has gone up over 50 percent in two years after the Canadian Government privatized the supply of Cobalt 60. In addition, Cobalt 60 sterilization plants face increasing costs associated with the storage, handling, and disposal of Cobalt 60.

Because electron-beam irradiation is forward-directed, it could sterilize medical products on a conveyor line instead of on a pallet, as is now done with ETO and Cobalt 60. Because a conveyor line system could be integrated with other production lines, it would further decrease costs and provide greater assurance of quality control.

Even with these advantages, however, the electrostatic and RF accelerator technologies available to date are not likely to supplant Cobalt 60 sterilization, due to their high operating costs. Science Research Laboratories (SRL), Inc., however, has developed a compact, modular linear accelerator with SDIO support that could break into this market. SRL's SNOMAD IV accelerator has a lower capital cost than competing accelerators and Cobalt 60; in addition, it also has much lower operating costs due to its reliability.

Production of PET Isotopes

In 1989, SDIO started the miniaturized Positron Emission Tomography (PET) accelerator program to reduce the cost of producing certain elements necessary for PET imaging. PET is important for medical applications because it images the body's chemical processes. It works as a diagnostic tool for cancer, brain disease, heart disease, and as an important research tool to enhance our understanding of the brain and mental disorders. The SDIO PET program builds on its large investment in accelerator technology for the SDIO neutral particle beam (NPB) program and will benefit both PET and SDIO, since PET and the NPB require similar accelerator technologies and the same large-scale manufacturing.

Currently, use of PET is largely limited to research uses because of the high cost of producing the tracer elements used for medical imaging. Large, high-power cyclotrons are used to produce these radiopharmaceuticals; while appropriate for research applications, where a wide variety of radiopharmaceuticals are needed in a limited supply, cyclotrons are extremely uneconomical for widespread clinical use. Thus, development of compact, inexpensive accelerators is generally considered the ideal way to introduce widespread clinical use of PET.

Accelerators now being developed for clinical uses have much lower power requirements than cyclotrons but still produce the four most common radiopharmaceuticals — fluorine 18, nitrogen 13, oxygen 15 and carbon 11. To get adequate quantities of the radiopharmaceuticals using low-power levels, the accelerators must produce high-current beams. SDIO is currently funding development of two small, low-power, high-current accelerators for the PET program: an RFQ system designed by SAIC and an electrostatic accelerator designed by Science Research Laboratories, Inc.

Other applications (electron-beam)

SDIO has sponsored the development of several compact electron-beam accelerators to drive free electron lasers. Non-medical applications of these accelerators are listed here.

- Coal-fired power plants can use electron-beams to reduce emissions of sulphur and nitrogen oxide, which cause acid rain, by converting them into the common fertilizers ammonium sulfate and ammonium nitrate. In addition to reducing acid rain, this method would allow power plants to use high sulphur-content coal. High-sulfur coal is the nation's most abundant fossil fuel; thus, this technique would greatly reduce our dependence on foreign oil without harming the environment.

- X-rays generated by electron-beams can treat ground and waste water contaminated with toxic substances. Most toxic wastes are artificial molecules that do not occur in nature. Electron-beams break these molecules into fragments, which afterward tend to recombine into simpler, non-toxic substances. The radiation dose required to accomplish this depends on the particular toxic material and the substance mixed with it. Dose requirements range from a small fraction of a Mrad (a measure of the amount of radiation absorbed) to over 10 Mrads, easily in the range of several SDI-developed accelerators.

- Electron-beam-generated x-rays can irradiate meats, fruits, vegetables and other perishable foods to prevent them from spoiling. This method provides a safer, non-nuclear source of radiation and could eliminate the need to treat food with potentially harmful chemicals.

- Electron-beams could treat the surface of materials. The technique can be used to harden plastics and other materials, improve the heat resistivity of wire insulation, control the quality of automobile rubber tires, and cure paintings or printing inks. It can also be used to bond metal-matrix composites, cross-link plastics and join ceramics.

- High energy electron-beams (on the order of 10 MeV) could be used to weld several types of materials, including HY100 (a high-strength steel used primarily in submarine hulls), aluminum, stainless steel, and titanium. Electron-beam welding has several advantages over other techniques:

  - The process can be done at atmospheric pressure. In other processes, parts need to be welded in a vacuum chamber. This makes high-energy electron-beam welding especially attractive for welding aircraft carrier deckplates, submarine hulls, nuclear power plant facilities, and other large-scale construction projects.

  - By penetrating further into the material at high energy densities, electron-beams create stronger, deeper welds. Electron-beams heat an area 5 mm into the material, while normal welding processes only heat the material's surface. As a result, normal welding processes cause heat stresses that weaken the material.

  - The radiation processes allow you to see the weld as the electron-beam forms it, resulting in better quality control.

<u>Other applications (neutrons)</u>

As part of the neutral particle beam program, SDIO has sponsored the development of particle accelerators that produce beams of neutrons by accelerating protons against a metal target. The interaction between the protons and the metal target produces a stream of neutrons that is used for these non-medical applications.

- The Federal Aviation Administration has developed a lightweight bomb detector that uses AccSys Technology, Inc.'s RFQ linac as a neutron source (SRL and SAIC have developed neutron sources for this purpose, as well: the SRL Tandem Cascade Accelerator [TCA] and SAIC's RFQ linac). The FAA bomb detector, which is currently undergoing testing, bathes luggage in low-energy neutrons. High-nitrogen-content explosives that may be in the luggage absorb the neutrons and emit a characteristic gamma radiation that can be detected by sensors in the system. Unlike other portable sources of neutrons which employ radioactive materials, the RFQ linac avoids radiation hazards and is lighter, because bulk shielding is not required. The compact size will allow FAA to employ bomb detectors in more airports, and give the airports greater flexibility of use, since the bomb detector can be more easily moved from terminal to terminal.

- The RFQ Linac also can provide neutrons for neutron radiography. This technique is used to detect elements that selectively absorb neutrons, including hydrocarbons (found in oil and O-ring seals) and hydroxides (found in corroded aluminum). Thus, it can inspect airplanes for cracks or corrosion, artillery shells for cracked explosive charges, and rocket engine propellants during test firing. It can also determine lubricant flow in aircraft engines and detect oil deposits.

- SDI accelerators could also change long-lived nuclear wastes into harmless isotopes (see figure 2). A process under development at Los Alamos National Laboratory would use a high-power, high-current accelerator to create an intense flux of neutrons. A molten salt would carry the nuclear waste through a tank of heavy water (water made up of the heavier hydrogen isotope deuterium), which slows down the neutron flux.

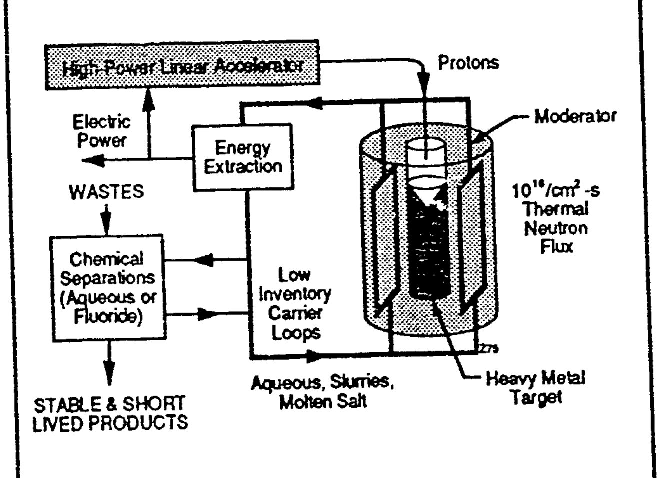


Figure 2. System for the Transmutation of Nuclear Waste

By slowing down the neutrons, the heavy water allows more nuclear waste to absorb the neutrons; the neutrons, in turn, spark a nuclear reaction that changes the waste into a new, stable isotope or into an unstable isotope that will quickly decay into a stable one. The molten salt, which has been heated up during this reaction, is then circulated out of the tank of heavy water. Once out of the heavy water, the molten salt can be used to generate electricity. Then, after the process is complete, chemical reactions extract the harmless isotopes out of the molten salt and replace it with more nuclear waste for another round of processing.

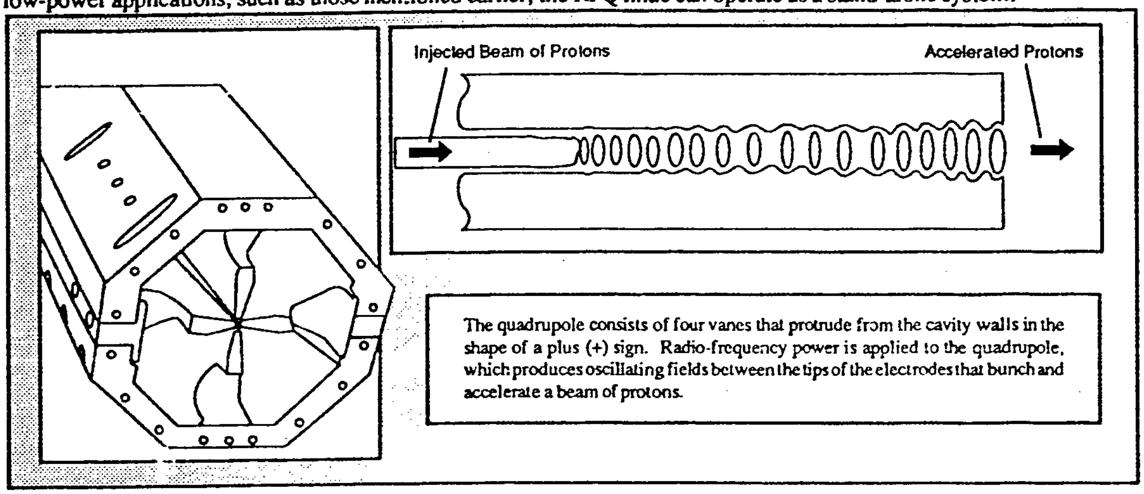
ACCELERATORS

Radio Frequency Quadrupole Linear Accelerator (RFQ Linac)

Soviet accelerator physicists developed the first RFQ linac in 1974. Since learning of this development in 1977, Western scientists have used this concept to replace the three-story-high electrostatic accelerator (current RFQ linacs are 3-10 feet long and 1-3 feet in diameter). The RFQ linac's body consists of a quadrupole cavity, with 4 electrode vanes that protrude from the cavity walls in the shape of a plus (+) sign. This cavity is designed to produce oscillating electric fields between the tips of the electrodes when radio frequency power is applied to it. The oscillating fields bunch, focus, and accelerate ions or protons, providing a high-quality, high-current beam.

RFQ linacs were initially developed to serve as the first stage of high-energy linacs used for physics research (and later for SDI neutral particle beams, cancer therapy facilities like Loma Linda, and the production of tritium). High-power linacs such as these require high-current ion beams accelerated to energies of about 1 MeV. Prior to the invention of RFQ linacs, very large electrostatic accelerators, which require complex beam-focusing systems, served this purpose.

An RFQ linac now serves as the initial stage in over 20 research facilities, including the European Center for Nuclear Research (CERN) facility near Geneva Switzerland. In addition, the RFQ linac will play an important role in the U.S. Superconducting Super Collider, both as the initial stage injector, and to calibrate many of its particle detectors. For other, low-power applications, such as those mentioned earlier, the RFQ linac can operate as a stand-alone system.



The quadrupole consists of four vanes that protrude from the cavity walls in the shape of a plus (+) sign. Radio-frequency power is applied to the quadrupole, which produces oscillating fields between the tips of the electrodes that bunch and accelerate a beam of protons.

Figure 3. The Four-Vaned Configuration of the RFQ Linac

Science Research Laboratory's SNOMAD IV

SRL developed the SNOMAD IV as part of an SDIO Small Business Innovation Research project to build an electron-beam driver for the free electron laser. A key feature of the SNOMAD IV is the all solid-state driver, which dramatically increases reliability; the SNOMAD IV can operate for 2-3 years (generating 10^{11} to 10^{12} shots) without maintenance, unlike other accelerators which must be serviced every few months. Also, since the SNOMAD IV would use six accelerator modules to produce the electron-beam energies necessary for bulk sterilization, mechanical breakdowns could be serviced with minimal down-time. A spare module could simply replace the affected module while someone serviced it. Finally, the SNOMAD IV has a completely computerized control panel that allows a technician to punch in the dose and run-time. This

ease-of-use reduces labor costs by eliminating the need for a staff of highly trained accelerator physicists.

The SNOMAD IV also produces much higher average currents than competing RF and electrostatic accelerators. The higher currents allow the accelerator to operate at optimal beam energies (8 MeV) without sacrificing throughput (average power). Beam energies much higher than 8 MeV are undesirable because medical products, when subjected to beam energies greater than 10 MeV, can become permanently radioactive. Because other accelerators have low average currents, they must sacrifice throughput to operate below this 10 MeV maximum.

Table 1. SRL's SNOMAD IV Compared to Competing Electron-Beam Accelerators

Characteristics	SNOMAD IV	RF Accelerators (AECL's IMPELA)	Electrostatic Accelerators (DYNAMATRON)
Average Power* (Throughput)	1 Megawatt	50 kilowatts	200 kilowatts
Beam Energy (measures penetration)	8 MeV	10 MeV	5 MeV
Average Current	0.125 Amps	0.005 Amps	0.04 Amps
Capital Cost	$2.5 million ($400,000/module)	$3.5 - 4 million	$1.5 - $4 million

* note: average power = beam energy x average current

Miniaturized Accelerators for PET

The SDIO-funded PET accelerators have been designed for easy maintenance, easy operation and low shielding requirements — all of which reduce operating costs for clinical PET radiopharmaceutical production. Cyclotron systems have long maintenance down-times — often forcing an operating schedule of four days on and three days off — because there is a long "cool-down" period for the radioactive materials before maintenance can be performed. The SDIO-funded accelerators have little — if any — cool-down period and less maintenance requirements in general. Also, a staff of accelerator physicists must operate cyclotrons, while a technician working at a computer terminal could operate the SDIO-funded accelerators.

Finally, the shielding requirements for the SDIO-funded accelerators are much lower. Because the SAIC RFQ linac accelerates Helium-3 particles instead of protons or deuterons, it has shielding requirements ten times lower than for cyclotrons. This is because Helium 3 particles produce very few neutrons when interacting with the target material, and therefore produce less hazardous radiation.

Table 2. Comparison of Accelerators for PET Radiopharmaceutical Production

PET Accelerators	SAIC RFQ design	SRL Tandem Cascade Accelerator (TCA)	Cyclotrons
Average Power	20 kW	37 kW	High
Beam Energy	8 MeV (accelerating He^3)	3.7 MeV (accelerating protons and deuterons)	Varies (depending on current produced) — up to 50-60 MeV
Average Current	300 microamps	1 mA	Varies
Capital Cost	under development (less than $1 million)	$750,000	$1-2 million
Weight	1,300 lbs.	1,200 lbs.	5-20 tons
Radiopharmaceuticals produced	all (^{11}C, ^{15}O, ^{18}F, ^{13}N)	all	all (plus others for research purposes)

Transmutation of Nuclear Waste Accelerator

Transmutation accelerators require extremely high-power proton-beams to produce adequate neutron-fluxes to change nuclear waste into stable by-products. The Los Alamos design — originally developed for tritium production (which requires much higher currents but similar power levels) — uses two pairs of injectors, each consisting of two RFQ linacs and two drift-tube linacs (DTL). The injector-produced proton-beams are combined into a 20 MeV beam using a funneled beam-launcher (see diagram). The 20 MeV beam is then accelerated through a coupled-cavity linac, producing a 1600 MeV beam with a current of 50-250 mA (55 mA for transmutation and 250 mA for tritium production).

These stages are designed to optimize particle acceleration at successfully higher velocities. Advances in high-current linear accelerator technology initiated by SDI's Neutral Particle Beam program have produced sizable improvements in the generation, acceleration, and handling of low-energy beams within the accelerator. Because efficient low-energy handling during the injector phase is key to creating a reliable, high-current, high-energy accelerator system, these advances have made the transmutation system possible.

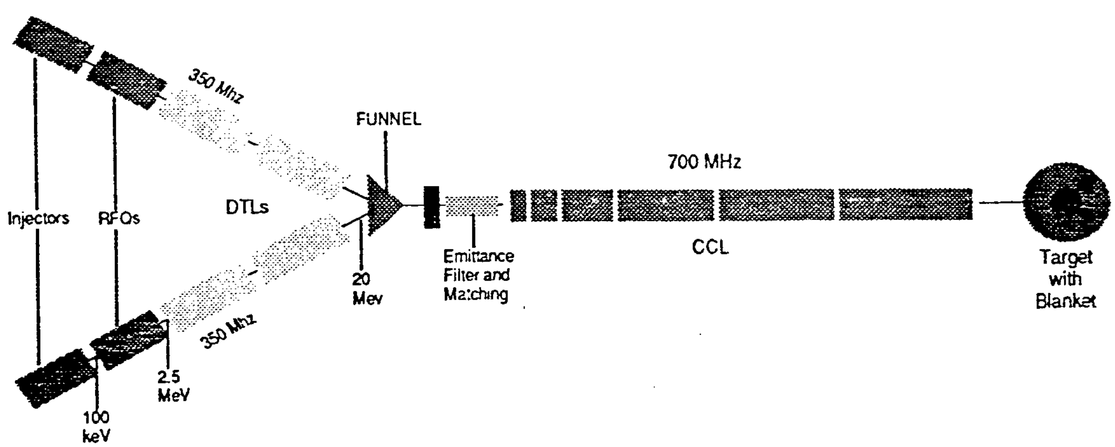


Figure 4. Proposed Accelerator for the Transmutation of Nuclear Waste

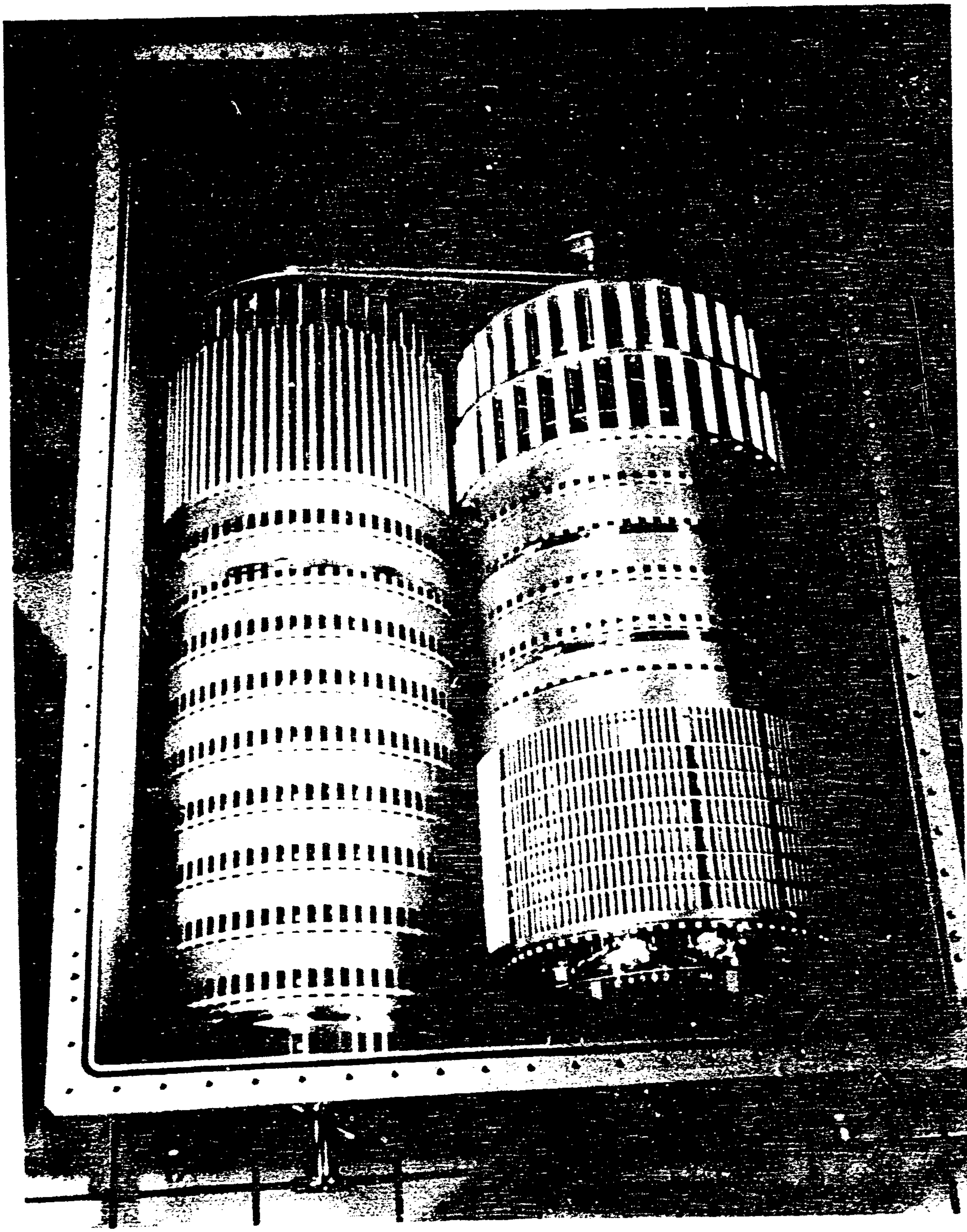


Photo #1: One Module of SRL's SNOMAD IV Accelerator

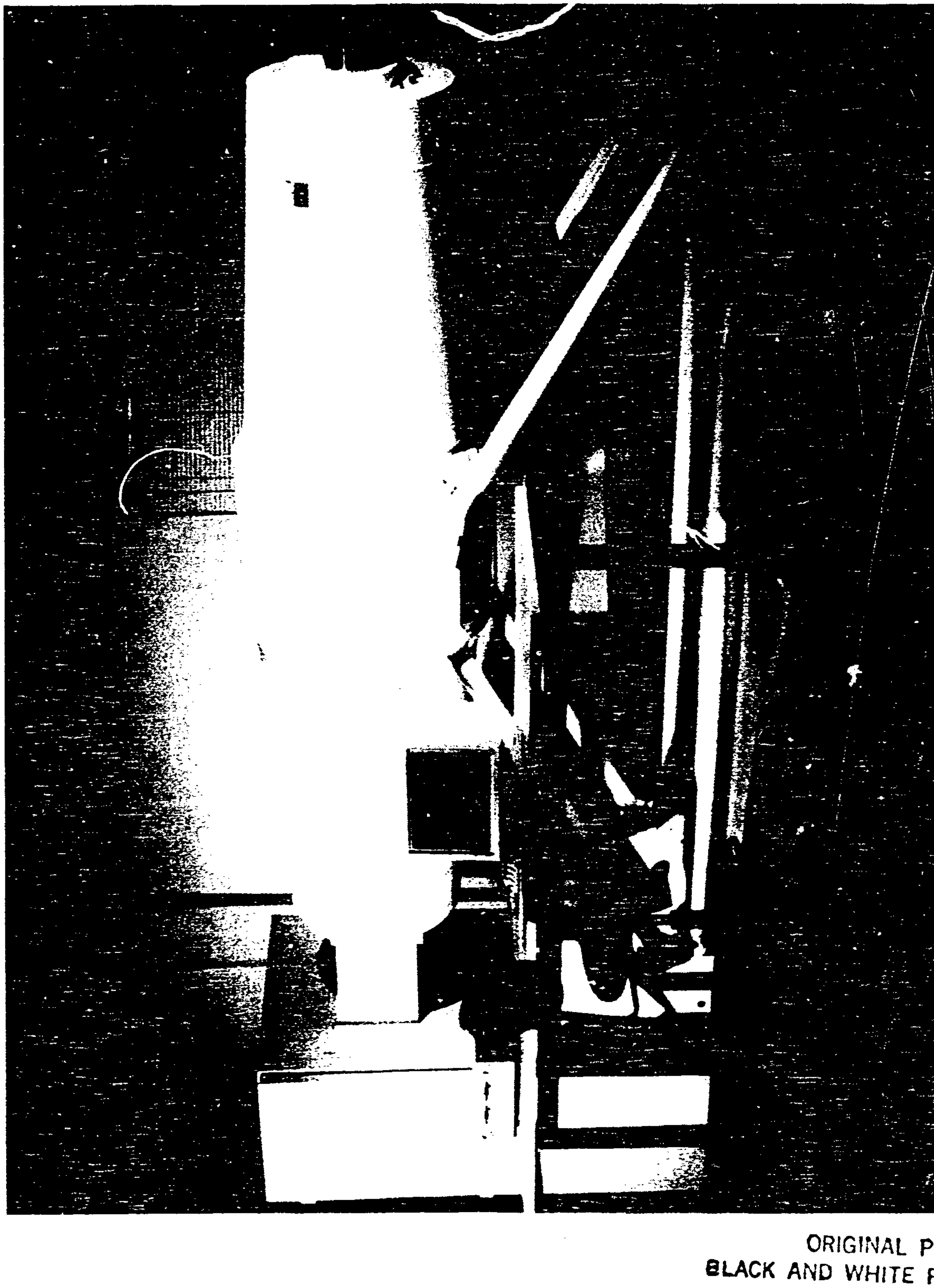


Photo #2: SRL's Tandem Cascade Accelerator

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